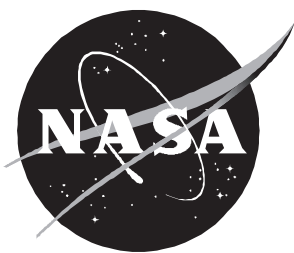


48-Inch Lidar Aerosol Measurements Taken at the Langley Research Center

July 1991 to December 1992

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Preface

This report summarizes measurements obtained using the ground-based 48-inch lidar system at the Langley Research Center in Hampton, Virginia, from July 1991 through December 1992. The data set extends the long-term ground-based lidar measurements of mid-latitude stratospheric and upper tropospheric aerosols at Langley to a database that includes 19 years of data.

NASA RP-1209 reports measurements obtained from May 1974 through December 1987. The present report covers a shorter, but very important period, since the stratospheric aerosol loading was greatly enhanced by the eruption of Mount Pinatubo in June 1991.

Summary

This report presents lidar data taken between July 1991 and December 1992 using a ground-based 48-inch lidar instrument at the Langley Research Center in Hampton, Virginia. Seventy lidar profiles (approximately one per week) were obtained during this period, which began less than 1 month after the eruption of the Mount Pinatubo volcano in the Philippines. Plots of backscattering ratio as a function of altitude are presented for each data set along with tables containing numerical values of the backscattering ratio and backscattering coefficient versus altitude. The enhanced aerosol backscattering seen in the profiles highlights the influence of the Mount Pinatubo eruption on the stratospheric aerosol loading over Hampton. The long-term record of the profiles gives a picture of the evolution of the aerosol cloud, which reached maximum loading approximately 8 months after the eruption and then started to decrease gradually.

Introduction

A ground-based 48-inch lidar system has been in operation at the Langley Research Center in Hampton, Virginia (37.1°N, 76.3°W), since May 1974. During this period, a number of volcanic eruptions have occurred which significantly increased the stratospheric aerosol loading. Measurements obtained by the 48-inch lidar on a semiregular basis (weekly when weather and cloud conditions permitted) have provided high-resolution vertical profiles; these measurements have resulted in a valuable long-term record of the mid-latitude upper tropospheric and stratospheric aerosol. Results of measurements covering the period between May 1974 and December 1987 have been reported by Fuller et al. (ref. 1). In addition to studies on volcanic eruptions, data obtained with the 48-inch system have been used in other scientific studies (refs. 2 and 3) on stratospheric aerosols (e.g., for comparison with satellite data).

During the period from 1988 to 1990, measurements obtained with the 48-inch lidar were sparse because of frequent failures of aging equipment. Since no extraordinary atmospheric events occurred, results obtained during that period are not presented in this report. In mid-1990, measurements with the 48-inch lidar were temporarily halted while several substantial modifications were made to improve the performance of the system. These improvements included relocating the instrument from a mobile platform to an indoor laboratory, upgrading the data acquisition system, and polishing and recoating the telescope mirrors. The modifications were completed

in the late spring of 1991, and routine operations were resumed in July of that year.

This report presents observations from July 1991 through December 1992; during this period, the global stratospheric aerosol was greatly enhanced by material produced from the eruption of the Mount Pinatubo volcano in the Philippines (15.1°N, 120.4°E) on June 15–16, 1991. November 16 marks the last day in 1992 on which data were taken. Either cloudy conditions or holiday vacations interfered with measurements for the remainder of the year.

These data, which are presented in a ready-to-use format, will be useful to researchers studying effects of the Mount Pinatubo aerosols on the global radiation balance and climate and on heterogeneous chemical processes in the stratosphere. This document, along with reference 1, provides a history of data obtained by the 48-inch lidar system. Plans are being made to make these data and future 48-inch lidar data available through the Distributed Active Archive Center (DAAC) at the Langley Research Center.

Symbols

The term $B(z)$ is used in this report for backscattering coefficient because it is more often used in the literature than $f(z)$.

$B_A(z)$	aerosol backscattering coefficient at z (equivalent to $f_A(z)$ in ref. 1), (km-sr) ⁻¹
$B_M(z)$	molecular backscattering coefficient at z (equivalent to $f_M(z)$ in ref. 1), (km-sr) ⁻¹
C	lidar system constant
R_{\min}	minimum value of scattering ratio
$R(z)$	aerosol lidar backscattering ratio at z
$S(z)$	lidar return signal from z
$T^2(z)$	two-way atmospheric transmittance between lidar instrument and z
z	altitude, km

48-Inch Lidar System

The data presented here were obtained with a lidar system consisting of a 48-in. (1.22-m) Cassegrainian telescope and a ruby laser that nominally emitted 1 joule per pulse at a wavelength λ of 0.6943 μm at a repetition rate of 0.15 Hz. The divergence of the transmitted beam is approximately 1.0 mrad, and the maximum receiver field of view is 4.0 mrad. The electronic bandwidth of the receiver is 1 MHz, which provides a 150-m vertical resolution.

Three photomultiplier tubes, electronically switched on (gated) at different delay times after laser firing, are used to provide a large dynamic range. The photomultiplier tube output signals are processed by 12-bit Computer Automated Measurement and Control (CAMAC) based digitizers and acquired by a personal computer. The data are archived on optical discs.

Lidar Profiles

The lidar backscattering ratio at altitude z is defined as the ratio of the total aerosol plus molecular backscattering to the molecular backscattering, and it is expressed by Russell et al. (ref. 4) as

$$R(z) = \frac{B_A(z) + B_M(z)}{B_M(z)} = 1 + \frac{B_A(z)}{B_M(z)} \quad (1)$$

where $B_A(z)$ is the aerosol backscattering coefficient, and $B_M(z)$ is the molecular backscattering coefficient, both in units of $(\text{km-sr})^{-1}$. The term $B_M(z)$ is calculated from temperature-pressure profiles obtained from radiosondes launched at Wallops Island, Virginia (120 km northeast of the lidar system), just prior to or just after lidar data collection. The backscattering ratio $R(z)$ is calculated by evaluating

$$R(z) = \frac{CS(z)z^2}{B_M(z)T^2(z)} \quad (2)$$

where $S(z)$ is the lidar return signal received from altitude z , $T^2(z)$ is the two-way atmospheric transmittance, and C is a lidar system constant determined by following the procedure of Russell et al. (ref. 4) and normalizing the right-hand side of equation (2) to an expected minimum value of R (R_{\min}) over a specified altitude range. The term $T^2(z)$ is calculated from a combination of radiosonde data-derived molecular extinction, model or lidar-derived aerosol extinction, and model ozone absorption. During periods of background or moderate aerosol loading, aerosol extinction can be adequately modeled. However, since the aerosol loading is greatly increased after major volcanic eruptions such as that of Mount Pinatubo, the aerosol extinction component of the atmospheric transmittance in such cases may be calculated directly from the aerosol backscatter. Equation (2) is then solved iteratively by successively using updated values for aerosol extinction.

Appendix A presents 70 scattering-ratio profiles obtained between July 1991 and December 1992. The tropopause height corresponding to each profile (as determined from the Wallops Island radiosonde) is indicated by an arrow. Each profile represents an average of approximately 100 to 200 laser shots. Note

that the scale of the horizontal axis has been changed several times in the progression of these profiles to accommodate the large variations in maximum scattering ratio. For example, profiles on July 14 and July 18, 1991, which show scattering-ratio values slightly greater than 1, are typical of background (nonvolcanic) conditions. These low scattering-ratio values indicate a relatively clean atmosphere, although one not as clean as in 1979 after a relatively long volcanically inactive period (fig. 1). In July 1991, the stratosphere had not fully recovered from the 1982 El Chichon eruption in Mexico (ref. 5). The small peak in scattering ratio (≈ 1.5) near the 15-km altitude on July 14 is due to a thin cirrus cloud at the tropopause. The profile from August 3, 1991, marks the first appearance of stratospheric aerosol from the Mount Pinatubo eruption. The Mount Pinatubo aerosol was observed between approximately 17 and 19 km, and the peak backscattering ratios ranged from 3 to 6 during most of August. On August 28, a much more intense aerosol layer was observed near a 24-km altitude, and the peak backscattering ratio exceeded 26. This higher altitude layer persisted throughout the winter and early spring of 1992 (ref. 5).

The profiles presented in appendix A show variations in profile shapes from one measurement to another, but the Mount Pinatubo aerosol layer generally grew in intensity until a maximum scattering ratio of 34 was reached on February 20, 1992. After this date, the peak scattering ratio gradually decreased as a result of dynamic processes in the atmosphere. The layer gradually broadened vertically, and the peak backscattering ratio occurred at progressively lower altitudes through the end of 1992.

Appendix B contains a numerical tabulation of the scattering ratio and backscattering coefficient versus altitude for each profile presented in appendix A. The values are reported at 0.75-km intervals to reduce the amount of data to a manageable size. The profiles were normalized to a scattering ratio of 1, which is a value that would be obtained if no aerosols were present at some altitude within the normalization region. Occasionally, the numerical values of the scattering ratio are less than 1, and the corresponding scattering coefficients are negative at altitudes where the measurements and/or meteorological data are subject to considerable uncertainty. This uncertainty happens when the minimum aerosol concentration occurs outside the normalization region. True minimum values of the aerosol backscattering ratio and backscattering coefficient should be considered 1 and 0, respectively.

Error Analysis

Derivation of scattering ratios is subject to a number of uncertainties arising from the measurements themselves and from the assumptions used in the data analysis. The random error in the scattering ratio contains contributions from signal measurement error, error in the correction for two-way transmittance, density errors, and error in the assumed value of R_{\min} . The magnitude of these errors is related to the amount of aerosol loading, the lidar wavelength, the proximity in time and space to a measured molecular density profile, the number of laser shots averaged together in a sequence, the background lighting conditions, and the models used for atmospheric attenuation. All these random errors can be measured or estimated as discussed by Russell et al. (ref. 4). This reference gives a detailed discussion of the lidar error analysis. However, systematic errors caused by imperfect system alignment, nonlinearities in the detectors and receiver response (ref. 6), and incorrect background measurement are hard to estimate and are not included in the error analysis. On all the lidar profiles presented in appendix A, $1\text{-}\sigma$ (standard deviation) random error bars are plotted to give an indication of the precision of the 48-inch lidar scattering ratio measurement.

The random error in the aerosol backscattering coefficient contains contributions from the same error sources as the scattering ratio. However, the scattering coefficient is more sensitive to the amount of aerosol being measured since it is proportional to $B_M(z)/B_A(z)$; in other words, as the amount of aerosol being measured becomes small, the relative error in backscattering coefficient becomes large. Measurements from the 48-inch lidar have been successfully compared with aerosol number concentrations measured with University of Wyoming dustsonde during balloon flights (refs. 1 to 3) and with *in-situ* particle measurements from the NASA ER-2 aircraft (ref. 7).

Integrated Backscattering

The integrated stratospheric aerosol backscattering I (in units of sr^{-1}) is defined as

$$I = \int_{h_T}^{30\text{km}} B_A(z) dz \quad (3)$$

where h_T is the height (in kilometers) of the tropopause. The numerical tabulations in appendix B show values of the integrated aerosol backscattering and the tropopause height for the profiles in appendix A. These values illustrate that the maxi-

mum aerosol loading over Hampton from the Mount Pinatubo eruption occurred in late February 1992.

An aerosol optical model was formulated using the size distribution and the index of refraction data from a six-channel dustsonde flight that was launched on February 13, 1992, at Laramie, Wyoming (41°N). By assuming that the aerosol characteristics determined from the dustsonde flight were representative of the bulk of the volcanic cloud, a factor for converting integrated backscattering to optical depth was calculated to be 45 sr (ref. 8). Using this conversion factor, a peak optical depth over Hampton of approximately 0.24 at $\lambda = 0.6943 \mu\text{m}$ was calculated. By comparison, the peak optical depth computed in the same manner after the El Chichon eruption was 0.13 (ref. 1).

Long-Term Record

The measurements obtained with the 48-inch lidar since May 1974 are summarized in table 1. This table lists the measurement date, the parameter (peak scattering ratio ($R - 1$), which is often called the backscattering mixing ratio), the altitude of the peak scattering ratio, and the integrated backscattering for each measurement. Figures 1 and 2 show the long-term record of the aerosol loadings. Figure 1 presents the peak scattering ratio, and figure 2, gives the integrated backscattering. The occurrences of major volcanic eruptions that injected material into the stratosphere are indicated on the time axes, and their influence on the stratospheric aerosol loading is evident. The El Chichon and Mount Pinatubo eruptions have produced, by far, the greatest enhancements to the stratospheric aerosol. The peak integrated backscattering from the Mount Pinatubo cloud was approximately twice that from the El Chichon cloud. This ratio is approximately equal to the ratio of calculated optical depths discussed above. Both of these eruptions have prompted numerous studies on volcanically induced aerosols in the stratosphere, including airborne lidar measurements. The 48-inch lidar measurements have provided valuable guidance in the planning of the airborne missions, and they have aided in the interpretation of aerosol observations (refs. 9 to 18).

The integrated backscattering provides a relative measure of the amount of aerosol above a given location. Figure 3 compares the integrated backscattering measurements at Langley following the eruptions of the Mount Pinatubo and El Chichon over an 18-month period. The initial rise in integrated backscattering is mostly due to a general poleward transport of the aerosol from the tropics where it was initially confined. Additional aerosols also may have

been formed via a gas-to-particle conversion. Note that the aerosol concentration immediately preceding the eruption of El Chichon was higher than that preceding the eruption of Mount Pinatubo. This higher concentration was perhaps due to residual aerosols from several smaller volcanic eruptions in 1980 and 1981. The first volcanic aerosol layer from El Chichon reached Hampton on May 10, 1982 (approximately 42 days after the first major eruption on March 28, 1982), whereas the first volcanic aerosol layer from Mount Pinatubo was measured 48 days after the eruption. These meridional transport times are comparable, especially since the first Mount Pinatubo aerosol layer could have arrived a few days earlier without being detected because of cloudy weather. Also, the two events occurred at different longitudes and during different seasons.

The integrated backscattering values measured for the first 100 days after each eruption are comparable. However, the Mount Pinatubo aerosol consistently exceeds the values measured after the El Chichon eruption for the period from 4 to 10 months following the eruption. The largest Mount Pinatubo integrated backscattering, 0.0053 sr^{-1} , occurred on February 20, 1992, which is 250 days after the eruption. The $1/e$ (where e is the base of the natural logarithm 2.718) decay times for the 9 months

following their respective peak loadings are approximately 7.3 months for the Mount Pinatubo eruption and 6.7 months for the El Chichon eruption.

Concluding Remarks

Stratospheric aerosols from the eruption of Mount Pinatubo in June 1991 were observed over Hampton, Virginia, on a regular basis between July 1991 and December 1992 by the Langley Research Center 48-inch ground-based lidar. Lidar scattering ratio profiles measured over this time period show that the Mount Pinatubo aerosol first arrived over the Hampton area in early August 1991. The peak scattering ratio and the integrated backscattering (indicative of aerosol mass loading) gradually increased from August 1991 through late February 1992, when maximum values were observed. The aerosol loading has been slowly decreasing since then. The peak integrated backscattering value measured in February 1992 indicates that the Mount Pinatubo eruption produced more stratospheric aerosol than any previous volcanic eruption since observations first started with the 48-inch lidar in 1974.

NASA Langley Research Center
Hampton, VA 23681-0001
April 19, 1994

Appendix A

Lidar Scattering-Ratio Profiles

This appendix presents the 70 48-inch lidar scattering-ratio profiles measured between July 1991 and December 1992. The arrow indicates the tropopause height corresponding to each profile (as determined from the Wallops Island radiosonde). These profiles correspond to the numerical tables presented in appendix B.

Appendix B

Tables of Scattering Ratio and Backscattering Coefficient Versus Altitude for Each Profile

This appendix contains numerical tables of scattering ratio and backscattering coefficient versus altitude for the profiles shown in appendix A. The terms HNORM and TROP stand for normalization height and tropopause height, respectively.

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Table 1. Summary of Lidar Measurements Taken From May 1974 to November 1992

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Table 1. Continued

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Table 1. Continued

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Table 1. Concluded

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Table 1. Continued

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Date	Peak		Integrated backscattering, sr^{-1}
	$R - 1$	Alt., km	

Figure 1. Peak backscattering mixing ratio versus time. (Long-term record of peak scattering ratio measured by 48-inch lidar at Langley Research Center; arrows indicate times of major volcanic eruptions.)

Figure 2. Integrated stratospheric backscattering versus time. (Long-term record of integrated stratospheric backscattering measured by 48-inch lidar at Langley Research Center.)

Figure 3. Integrated backscattering versus time: Mount Pinatubo compared with El Chichon. (Backscattering measured by 48-inch lidar at Langley Research Center following 1982 El Chichon and 1991 Mount Pinatubo eruptions.)

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